The 23rd William Blum Lecture
Presented at the 69th AES Annual Convention in San Francisco, California
June 21, 1982

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ABSTRACT

Four aspects of material science pertinent to electroplating are considered in this, the text of the 23rd William Blum Lecture, presented by the 1981 recipient of the AES Scientific Achievement Award. The discussion addresses the ways in which epitaxy, twinning, dislocations and nucleation and growth of electrodeposits determine the deposit structure, which, in turn, is influenced by the deposition variables and the composition of the plating solution. The effects of structure on properties such as adhesion, brightness, corrosion resistance, ductility, electrical conductivity, hardness, internal stress, leveling capability, magnetics, strength and wear resistance are considered.

Introduction

Material science is concerned primarily with the relationships of the structure of solids and their properties. Dr. William Blum, in whose name this lecture has been prepared, was one of the pioneers in applying the principles of material science (even though it was not so named in his time) to electroplating. His book[1] contains a number of photographs of structures of electrodeposits, and he also wrote about the properties of electroplated metals.[2] One of the first AES-sponsored research projects at the National Bureau of Standards dealt with the properties of electrodeposited nickel.[3] Several recipients of the AES Scientific Achievement Award, in particular Professors Harold Read[4] and Hellmuth Fischer,[5] discussed aspects of the material science of electrodeposits in their William Blum Lectures in 1966 and 1969, respectively.

I was Professor Read's student and he was therefore responsible for my interest in plating. Dr. Blum and Professor Fischer encouraged me to continue my research in the field. The support of the American Electroplaters' Society helped me to carry out much of the research that is the basis of this presentation. I also wish to acknowledge the contributions of my former and present students. Most of them are listed in the references as co-authors of my papers.

For this presentation, I have selected four aspects of the structure of materials pertinent to electroplating. I will try to show how the properties of electrodeposits depend on these structural features and how they, in turn, are related to the plating conditions.

Epitaxy

Epitaxy is the continuation of the crystal structure of the substrate by the deposit. Crystal structures are arrangements of atoms in a regular pattern, which is repeated over relatively long distances in the three dimensions. The volume of material in which the atom arrangement is repeated in a regular way is a crystal. In solids composed of many crystals, they are also called grains. Most workpieces, or substrates, for plating are composed of many grains. The electrodeposit will try to copy the grain structure of the substrate surface. Then, a given atom plane of the deposit will be parallel to one of the substrate grains, a condition known as epitaxy. Therefore, the epitaxial deposit initially has the same grain size as the substrate.

Epitaxy is favored when deposition occurs on a clean, metallic substrate. On surfaces covered with difficult-to-remove oxides (*e.g.*, as on stainless steel), epitaxy is not readily achieved. Also, when the current density is high, the atoms of the depositing metal, which arrive at the substrate in very large numbers, find it difficult to arrange themselves so as to fit on the substrate structure. Nonepitaxy is then favored.

There is considerable evidence[6-11] that epitaxial deposition on very smooth substrates occurs initially by the lateral (*i.e.*, parallel to the surface) spreading of atom layers. Such layer growth was also observed when nickel (from Watts-type baths) was plated on copper[6-9] and gold (from sulfite solutions) was deposited on electropolished silver[10] and copper[11] substrates. The gold layers on silver persisted to the greatest thickness, probably because the difference in interatomic spacing, which is called the misfit, is very small. The misfit is one of the factors responsible for internal stress, which generally attains its highest value during the initial deposition. If the deposit has a smaller interatomic spacing than the substrate, as is the case when nickel is plated on copper, the initial internal stress is tensile.[12] The tensile stress results because the nickel atoms are pulled apart to fit on the structure of the copper substrate. When gold is plated on copper, the initial deposit is in compression because the deposit has a larger interatomic spacing than the substrate. Gold plated on silver is initially stress-free. Epitaxial deposits usually do not crack, even under relatively high tensile stress. It was found[13] that when very thin nickel films, which were originally epitaxially deposited on copper, were tensile tested without their substrates, considerable local plastic deformation preceded fracture. As such plastic deformation cannot occur in thin deposits still attached their substrate, a very large internal stress is required to cause fracture.

Under practical plating conditions, epitaxial growth occurs - except possibly for the very initial stage - by the development of three-dimensional forms, the lateral dimensions of which are approximately equal to their thickness. These three-dimension forms are pictured in Fig. 1. They have been named TEC, which stands for three-dimensional epitaxial crystallites. The effects of TEC on the properties of electrodeposits were extensively investigated under an AES-sponsored research project.[14-17] TEC probably form because of "bunching," which occurs when foreign substances (*e.g.*, molecules of additives to the plating solution) impede the lateral spreading of atom layers of the deposit. If one layer is stopped, others on top of it cannot overtake it and TEC are formed. The growth process now occurs by the formation of many TEC and their joining together - *i.e.*, coalescing into layers of deposit. There is evidence[18] that the formation and coalescence of TEC comprise the principal growth mechanism in practical plating.

The coalescence of TEC was found under AES-sponsored research[12] to be a factor contributing to the high internal stress observed during the early stages of deposition. TEC that form in close proximity to others can reduce their surface energy by being pulled together into larger units. This process probably occurs before the spaces between the TEC are completely filled with deposited material. It has been proposed[12] that this process can lead to bending of the deposit, indicative of stress. However, the stress results because the substrate tries to prevent the curvature. A hypothesis about internal stress as affected by different addition agents in the plating solution is also proposed based on TEC coalescence. Some additives are capable of stopping a whole plane of atoms from spreading laterally and thereby causing TEC to have smooth, planar side walls such as those illustrated in Fig. 1. When other additives (*e.g.*, saccharin) are present in nickel plating solutions, only small ions become incorporated.[19] The deposit layer then can probably spread laterally around these small ions, and TEC with rough side walls then develop. As TEC with smooth side walls can be pulled together to a greater extent, a larger tensile stress results. TEC with irregularly shaped side walls can make contact only at asperities, resulting in less pulling together and a lower tensile stress. When only asperities join, voids develop.[20] If these voids become filled with hydrogen, an expansion of the layer occurs, resulting in a compressive-stress contribution. This stress, depending on its magnitude and that of the tensile contribution, can result either in the reduction of the net tensile stress or a net compressive one.

The brightness of an epitaxial deposit depends on the smoothness of its surface. As long as the height difference between asperities and crevices (*i.e.*, hills and valleys) is less than the wavelength of light, the surface is bright. If the substrate surface is highly polished, the initial deposit layer, which copies its structure, is also bright. Even if the TEC, which form the deposit layer, have not yet coalesced, the crevices between them are usually not deep enough to cause a loss of brightness. However, as an epitaxial deposit becomes thicker, larger structural features such as hillocks, pyramids, ridges and blocks develop on the growing surface. These structures are tall enough above the rest of the surfaces to cause loss of brightness. Certain addition agents in the plating solution can cause pyramids to become truncated and to decrease the height of the blocks and ridges. In this way, the deposit surface is smoother and brighter. Such is the case in so-called semi-bright deposits. The thickness of the deposit may vary on grains of different orientations. Generally, when a certain atom plane is parallel to the surface, more TEC form on it than on others. Such preferentially oriented grains grow outward (*i.e.*, into the plating solution) at a faster rate. As they can also spread laterally, they tend to cover the slower-growing grains. They do so until they impinge on other faster-growing grains. In this way, a large portion of the surface of the deposit consists of grains having the preferred orientation. The phenomenon of faster-growing grains was observed by Dr. Blum[1] many years ago.

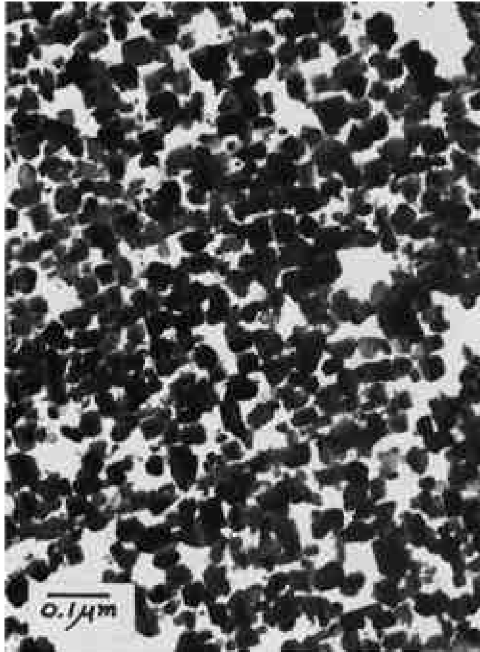

Figure 1 - Transmission electron micrograph of three-dimensional epitaxial crystallites (TEC) on gold deposit.

Figure 2 - Transmission electron micrograph of non-epitaxial nuclei (gold).

Nucleation and growth

Another important concept of material science pertinent to electrodeposition is nucleation and growth. Here, nucleation is the joining of groups of atoms to start new grains. The concept is therefore applicable to the formation of nonepitaxial deposits. The nuclei of nonepitaxial deposits, shown in Fig. 2, are three-dimensional forms that resemble TEC. They differ from TEC in that each has a different orientation from its neighbors. All TEC that form on a particular substrate grain have essentially the same orientation.

In crystalline deposits, the orientation of the nuclei is generally random. Under many plating conditions, as was the case in epitaxial deposits, grains with a certain orientation grow outward (*i.e.*, perpendicular to the surface) at a faster rate than others. Again, these faster-growing grains also spread laterally, covering the slower-growing ones until they impinge on other faster-growing ones. In this way, the deposit surface tends to be composed mostly of grains having a certain plane of atoms parallel to the surface. However, a particular direction or row of atoms lying in this plane is generally randomly oriented in the different grains. When a certain plane is preferentially parallel to the surface, but the directions in it are randomly oriented, a fiber texture is said to exist.

Fiber textures are indirectly related to many of the properties of electrodeposits because they are indicative of the degree of inhibition to growth and therefore of the grain size and shape. The principal growth inhibitors are (1) additives to the plating solution and (2) products of various reactions such as those that can occur during nickel plating because of hydrogen evolution, which raises the pH and results in the formation of basic compounds. Addition agents also frequently undergo chemical reactions and form other growth-inhibiting species. Uninhibited growth is very rare under practical plating conditions. But it would be characterized by a fiber texture such that the plane in which the atoms are packed most closely would be parallel to the surface.[21] As growth becomes more inhibited, different fiber textures develop. There are ranges of values of the plating variables (*i.e.*, pH, current density, bath temperature and degree and type of agitation) in which a particular fiber texture is observed.[21,22] These fiber textures may be different for various plated metals and also depend on the type of plating solution. The presence of addition agents in the plating solution, sometimes even in very small amounts, can drastically shift the ranges of the variables in which a particular fiber texture exists.[22]

Fiber textures indicative of slightly inhibited growth are associated with relatively large grain sizes, like those in a copper deposit from a sulfate solution. In deposits that are initially non-epitaxial, most grains are covered by relatively few faster-growing ones[23] with increasing thickness, so that considerable lateral spreading is possible before it is restricted by other grains. Therefore, the grain size in the plane of the surface is quite large. Growth perpendicular to the surface is practically unrestricted. One grain therefore can extend throughout the deposit thickness. The grains have a columnar shape when the cross section of a deposit is viewed microscopically. The ends of these large columnar grains are characterized, as was already pointed out for initially epitaxial ones, by the presence of pyramids, ridges or blocks, resulting in a relatively dull appearance.

Fiber textures indicative of more inhibited growth are associated with smaller grain sizes. The restriction to growth perpendicular to the surface results in the nucleation of new grains in relatively large numbers. (This is the case for nickel deposits from a bath containing additives.) Thus, the faster-growing grains cannot spread laterally to any large extent before being restricted by others. As outward growth is less restricted, the grains are still columnar. When a whole layer of small columnar grains is stopped from growing outward by inhibiting chemical species and new grains have to be nucleated, the boundaries appear in a cross section as lines parallel to the surface. The lines result in the so-called banded structure.[24] Under conditions of very high inhibition, such as those encountered when plating alloys like nickel containing more than 25 percent molybdenum, outward growth is so severely restricted that there are no faster-growing grains. The orientation of the grains is then random and they no longer have a columnar shape (*e.g.*, in chromium deposits.

In order for a deposit to be specularly bright, it has to be fine grained. The exception is the already-discussed case of a thin epitaxial deposit on a polished substrate. The ends of small grains are generally hemispherical or pyramidal. When grains are very small, the height difference between the center and edge is generally less than the wavelength of light so that there is no loss of brightness. The surface of a bright deposit is shown on the left side of Fig. 3. Sometimes, outward growth is locally more inhibited, resulting in crevices deeper than the wavelength of light and therefore a loss of brightness. The right side of Fig. 3 shows a deposit having surface crevices and which therefore has a hazy appearance. Crevices can also surround groups of many small grains. Such crevices have been mistaken for the boundaries of large grains.

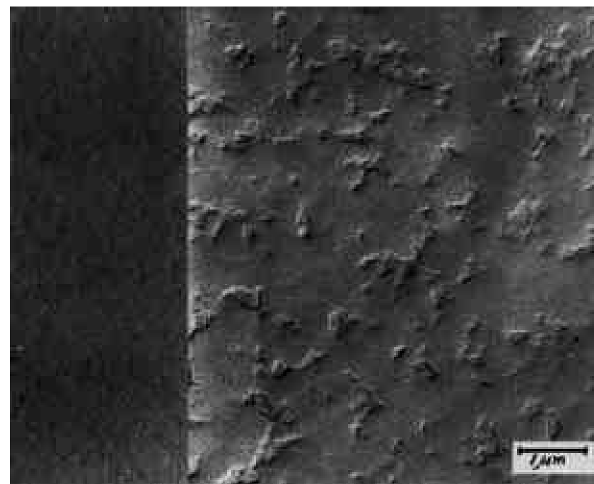

Figure 3 - Left side shows the surface of a bright nickel deposit; right side shows the surface of a hazy deposit with crevices.

Another property of electrodeposits, the leveling capability - which is essentially the opposite of crevice formation - is also associated with local inhibition to growth. But in this case, the growth inhibition occurs primarily at protrusions above the surface.[25,26] By impeding outward growth at the protrusions, the recessed areas receive a thicker deposit and leveling results.

Small-grained deposits tend to be harder and more brittle. An initially nonepitaxial deposit is therefore more likely to crack under a high internal stress, as was found in the current AES-sponsored research project.[27] A small grain size is also associated with a higher coercive force in plated magnetic materials. The coercive force is the field necessary to switch the magnetization.

Wear and electrical contact resistance are properties that depend on the surface structure.[27] Adhesive wear results from the bonding of asperities on opposing surfaces. During sliding of the surfaces over each other, these bonds are broken again. If the fracture does not occur at the original bond, one of the surfaces experiences a loss of material, or wear. In some cases, fracture can occur in both sides of the original bond and then both surfaces lose material. The particles thus formed can cause abrasive wear by plowing the surfaces. Wear can be reduced when the surfaces have fewer asperities - *i.e.*, when they are smooth. Between smooth surfaces, the actual area in contact is greater; therefore, the electrical resistance is smaller. Also, when deposits are relatively soft and ductile, protrusions tend to be smeared when surfaces slide over each other, thereby increasing the contact area. Oxides, which increase the electrical resistance, are brittle. During the smearing, oxides fracture, bringing fresh metal in contact. The contact resistance is then further reduced.

The ability of a deposit to protect the substrate from corrosion is also a structure-dependent property. As already discussed, fine-grained deposits are more susceptible to cracking under internal stresses. The substrate under the cracks is not protected. The factors that favor nonepitaxial growth can also cause gas porosity and voids to form at the interface between the substrate and such deposits.[28] Areas on the substrate that are not electrically conducting, either because of soils, oxides or nonmetallic inclusions, receive no deposit, which results in porosity. In thin deposits, voids may extend throughout the thickness and leave the substrate unprotected. With increasing deposit thickness, lateral spreading generally results in the closing these pores. However, voids in the deposit-substrate interface can be the start of fracture, leading to the loss of adhesion.

The corrosion resistance of the deposit itself is also related to the surface structure. Grain boundaries tend to corrode preferentially. If there is a range of grain sizes, the fine-grained region tends to corrode.[29] The crevices in fine-grained deposits also corrode preferentially. The grains in the crevices are even smaller than in the rest of the deposit and they also have a different chemical composition because of the greater incorporation of addition-agent products.[24]

The material-science concept of nucleation and growth is also applicable to the recrystallization of electrodeposits. Recrystallization in this case is a rearrangement of the grain structure after the deposition process is completed. Recrystallization usually occurs as a result of exposure to elevated temperatures. Deposits are held at elevated temperatures (*i.e.*, annealed) to soften them and increase their ductility. The relief of internal stress is another reason for annealing deposits. However, stress can be substantially relieved by annealing at lower temperatures than those required for recrystallization. Recrystallization of some electrodeposits can render them more brittle. For example, bright nickel, which has a relatively high sulfur content resulting from the codeposition of addition-agent products, forms a brittle sulfide at the boundaries of recrystallized grains. Also, during annealing, there is interdiffusion between the substrate and the deposits - *i.e.*, atoms of one move in to the other. Such interdiffusion can lead to better adhesion. However, if it results in the formation of new brittle compounds, adhesion is adversely affected.

In fine-grained deposits, recrystallization results in the formation of new, larger grains. Recrystallization occurs by a rotation, so as to align the atom rows in neighboring grains.[30] In larger-grained deposits, new grains are nucleated and then their boundaries move, expanding their size at the expense of the original ones. In fine-grained deposits, recrystallization occurs at relatively low temperatures. Fine-grained nickel deposits recrystallize at temperatures as low as 250°C.[30]

Twinning

A twin is a volume of material in which the atom arrangement is the mirror image of that of the grain surrounding it. Twins develop in electrodeposits due to several causes. Twinned regions on the surface of the substrate may be copied by epitaxial deposits. Slight misplacements of the atoms can result in twin formation, as illustrated in Fig. 4. Figure 4(a) shows the normal buildup of atom layers. The top layer is slightly misplaced in Fig. 4(b). In Fig. 4(c), another atom layer is shown misplaced and then two additional layers are shown as having been laid down in the normal sequence. If mirrors were placed at the third and fifth atom layer, as illustrated in Fig. 4(c), the twinning relationship would be evident, especially for the black balls. Actually, most twins are considerably thicker than the three atom planes shown in Fig. 4(d). For the crystal structure illustrated in Fig. 4, twinning is seen to occur on the plane in which the atoms are most closely packed. There are only specific atom planes on which twinning occurs. The misplacement resulting in twinning can occur due to the size difference between addition agents, their reaction products or other foreign substances, and the atoms of the plated metal.[31] Foreign substances therefore have a pronounced effect on twinning in electrodeposits. Planes of atoms can also be nucleated in the misplaced positions.[7] The misplacement can result from an applied stress. Twinning can also occur during recrystallization.

The change of grain orientation, such as that which occurs when an epitaxial deposit changes to a nonepitaxial one, frequently involves twinning.[32-35] When the fiber texture changes with deposit thickness, it occurs often by twinning.[21,37] The orientation change results when the atom planes, instead of assuming the usual relationship again as they did on the fifth layer in Fig. 4(c), are again misplaced.

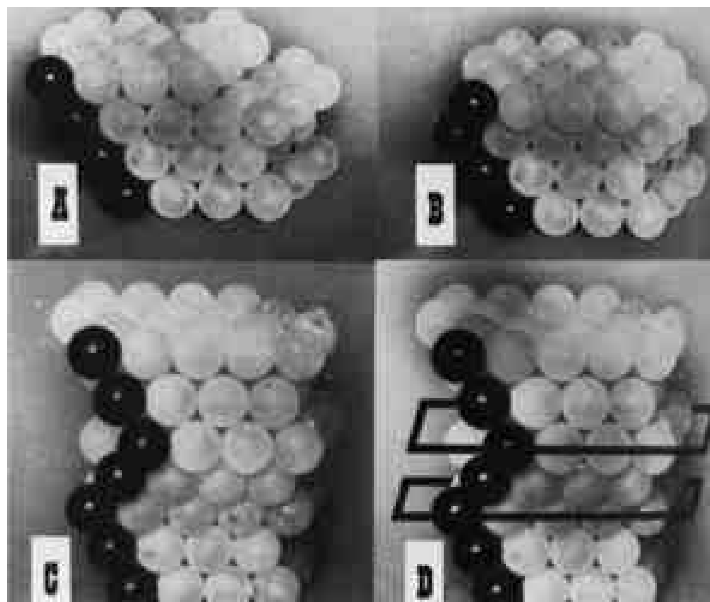

Figure 4 - Schematic representation of twinning.

By repeated twinning, various grain-orientation changes can be accomplished. The effects on epitaxy of the substrate-grain orientation and various foreign substances such as addition agents in the plating solution can be explained in terms of twinning. An important consideration is whether the atom plane on which twinning can occur is exposed on the surface. It has been found[28] that nickel plated on an etched copper substrate was nonepitaxial where there were pits. On a polished substrate, the deposit was epitaxial. Evidently, the twinning plane was exposed in the pits, but not on the polished surface. In AES-sponsored research,[18,36] the transition to nonepitaxy was found to occur on hillocks where the twinning plane was exposed. The grain orientation and the type of surface features (*e.g.*, pyramids, ridges and blocks) that form determine whether the plane on which twinning occurs is exposed. The foreign substances in the plating solution can then cause the misplacement on these planes that results in twinning. Also, at a high current density, there is a greater probability that planes of atoms are nucleated in the misplaced positions[32] because they arrive at the depositing surface in great numbers. Thus, when the twinning plane is exposed because of (1) certain grain orientations and surface structures of the substrate and (2) particular fiber textures of the deposit and in the presence of foreign material in the plating solution and at a high current density, frequent changes of grain orientation with deposit thickness occur. Such a condition therefore results in thin epitaxial or nonepitaxial deposits and also in relatively short columnar grains. Twinning thus affects those deposit properties that have already been shown to depend on epitaxy and on grain size and shape.

Twinning was found to be the principal mechanism of plastic deformation in very thin electrodeposits in the current AES research project[13] as well as in others.[38] The considerable plastic deformation observed prior to fracture in thin epitaxial deposits occurred primarily by twinning. This misplacement of atom planes due to an applied stress can only occur within a grain. Therefore, in very fine-grained deposits, twinning is severely limited. As was already pointed out, fine-grained deposits have been observed[13] to fracture without any appreciable prior plastic deformation.

Twins also have a role in the formation of structural features that grow on the surfaces of electrodeposits. They are involved in dendrite formation[39] and certain types of pyramids such as those with three or five sides.[37,40] Even very small three-dimensional forms, which develop during the initial stages of electroless copper plating, have been observed to contain twins.[41] Twins also form from TEC coalescence.[16] The boundaries of twins are susceptible to corrosive attack.[42]

Dislocations

Dislocations are a fourth feature of the structure of materials relevant to electrodeposits. Dislocations are also atom misplacements. While dislocations arise due to a number of causes, they can be illustrated in terms of an applied force moving part of a plane of atoms over another, as seen in Fig. 5. Dislocations are the boundary lines between the misplaced and the not-misplaced portions. In the two-dimensional model, the dislocations are the ends of extra atom rows indicated by arrows. In three dimensions, the dislocations shown here would be lines - *i.e.*, the ends of extra planes of atoms extending out of the picture of Fig. 5. Thus, the dislocations would be straight lines perpendicular to the applied force. However, particularly in electrodeposits, most dislocation lines are curved - *i.e.*, inclined to the applied force. Figure 5 also illustrates how the movement due to an applied force through a crystal results in plastic deformation. In Fig. 5(d), it is seen that the top portion of the crystal has been permanently displaced by two interatomic spaces with respect to the bottom. This is a plastic-deformation process called slip. It is thus seen that dislocations have an important role in determining the mechanical properties of materials.

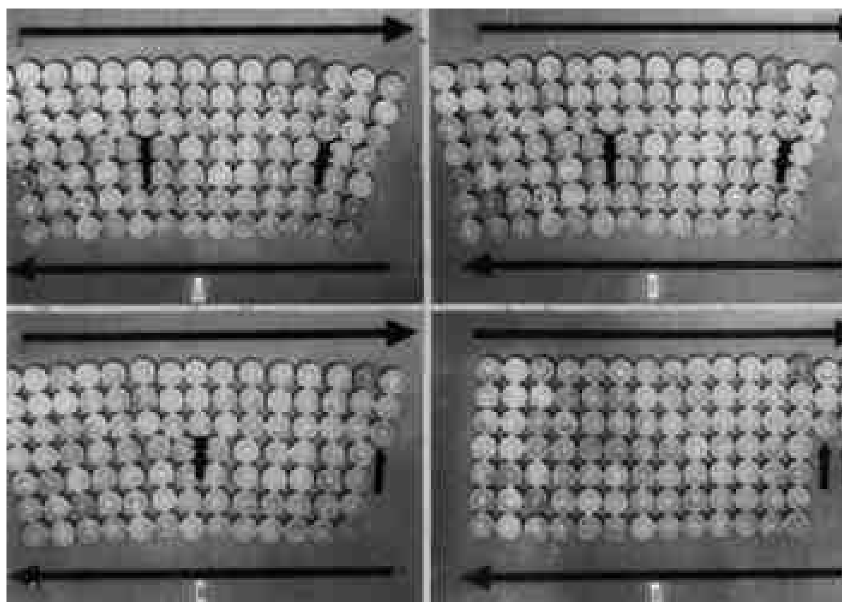

Figure 5 - Schematic representation of dislocation motion caused by applied shear stress.

Electrodeposits in general contain more dislocations than metals produced by other means. A typical dislocation structure in a nickel deposit is shown in Fig. 6. The dislocations are the dark-line segments and originate primarily during deposition. It appears that dislocations present at the substrate surface are not continued into the electrodeposit, even if it is epitaxial.[43] However, the generation of dislocations already has been reported[9] in the very thin continuous layer of the deposit that covers the substrate in the initial stages of epitaxial growth. Additives in the plating solution affect the number, length and curvature of the dislocation, showing that even in the very early stages of epitaxial growth, the substrate is not the only influence.[44]

The difference in the interatomic spacing between the substrate and the deposit (*i.e.*, the misfit) also results in a network of dislocations. They relieve the strain[12] when the extra atom planes act like little wedges. Dislocations can also originate from the coalescence of TEC[16] or larger epitaxial growth forms[45] when there are slight misorientations between neighbors. The dislocations can compensate for the misorientations.

As already mentioned, dislocations have a profound effect on the mechanical properties of materials. The resistance offered by a material to plastic deformation, which is equivalent to making it more difficult for dislocations to move, is its yield strength and is also related to its hardness, though in a more complicated way. The movement of dislocations is plastic deformation, as was illustrated in Fig. 5. Obstacles to dislocation motion are the sources of yield strength and hardness: grain boundaries, twin boundaries, other dislocations and atoms or atomic groups of a different size from those of the matrix. Because of the change in orientations at grain and twin boundaries, dislocations cannot cross them. Therefore, as already mentioned, small-grained

deposits are harder. The deposition variables and the composition of the plating solution probably affect the strength and ductility, mainly via the grain size. Dislocations, especially those that are stuck for various reasons, restrict the movement of other dislocations. Therefore, electrodeposits that generally contain more dislocations than metal produced by other means are harder. During plastic deformation, more dislocations are generated. Hence, plastic deformation results in a hardness increase. During recrystallization, the number of dislocations is reduced and the material becomes softer. The interference of foreign atoms with dislocation movement is a reason for the higher strength and hardness of alloys over those of pure metals.

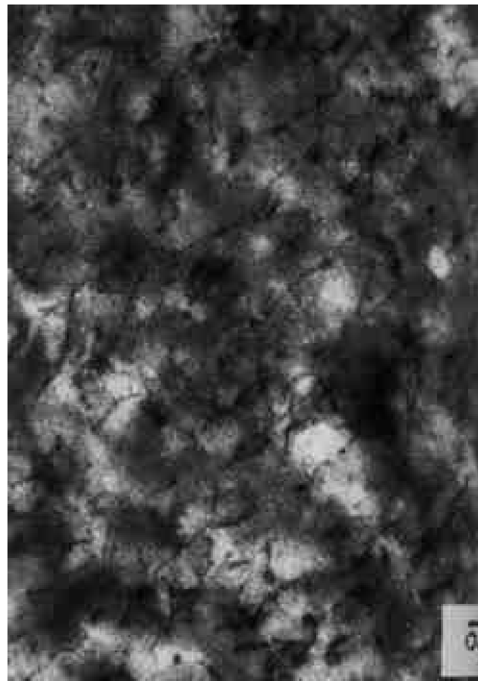

Figure 6 - Transmission electron micrograph of dislocations in a nickel electrodeposit.

The ductility (*i.e.*, the degree of plastic deformation that can occur before fracture) is also affected by the dislocation structure. Ductile materials such as copper plated from a pure acid sulfate solution fracture when the dislocations, which are created by the considerable preceding plastic deformation, get tangled.[46] The fracture originates in these tangles. In more brittle materials, fracture starts at defects such as pores, surface scratches, notches and foreign-particle inclusions. At these defects, the applied stress is higher than elsewhere and when it cannot be relieved by plastic deformation (*i.e.*, dislocation motion), fracture occurs. Thus, the ability of dislocations to move promotes ductile behavior. The brittleness of some electrodeposits results from the obstacles to dislocation motion already discussed and their tendency to contain some of the defects that start fracture.

Concluding remarks

An attempt has been made in this presentation to show that the principles of material science can be used to explain how the various structures of electrodeposits develop and how they determine their properties. The understanding that has been gained is to a great extent responsible for changing plating from art to a science. To this end, AES-supported research projects have made significant contributions. The science of electroplating has resulted in improvements in the properties of the deposits and in new applications.

However, much remains to be done. The role of hydrogen is poorly understood. This element appears to have a great effect on the properties of many deposits. The electrodeposition of alloys is an open field for research; electroplating offers a unique way of producing some alloys. Plating from nonaqueous electrolytes has received relatively little attention. A gulf exists between material scientists who study the structure and properties of electrodeposits and the electrochemists who investigate the

reactions and the plating processes. Bridging that gulf is one objective of the current AES-sponsored research project under my direction.

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About the author

Born in Neunkirchen, Germany, **Dr. Rolf Weil** came to the U.S. in 1940. He attended Carnegie Institute of Technology in Pittsburgh and received B.S. and M.S. degrees in metallurgy in 1946 and 1949, respectively. During this period he was employed as a metallurgist at Duquesne Smelting Corp.

He began work toward his Ph.D. in 1949 as a graduate assistant to Prof. Harold Read at the Pennsylvania State University. His doctoral thesis, accepted in 1951, was the first study of electrodeposition using electron microscopy. He then worked as a metallurgist at Argonne National Laboratory and Picatinny Arsenal. After two years of service in the Army, Dr. Weil joined Stevens Institute of Technology in Hoboken, NJ, as an assistant professor. He continued the research started at Penn State, became an Associate Professor in 1961, and was named Full Professor in 1967.

His work led to the establishment of a highly successful research program for electrodeposition at Stevens Institute. At the time, few universities had such an active program in this area. Under his direction, numerous students have received M.S. and/or Ph.D. degrees. Many of his associates have been employed by industrial laboratories and continue to make valuable contributions to the advancement of the finishing industry.

One of Dr. Weil's most significant achievements was his explanation of how the structures of electrodeposited metals develop, and how structure is related to the properties of a deposit. As a metallurgist, Dr. Weil approached this question from the perspective of analyzing the deposit rather than the chemical composition of baths. Using electron microscopy, he was able to resolve the grain structure of bright nickel deposits, and formulated the first theory relating surface morphology and brightness.

Early in his career, Dr. Weil noted the effects of sulfur-containing brighteners on the corrosion of nickel, a relationship important to the development of duplex nickel coatings. Other research defined the structure of the palladium-tin activator used for electroless plating and revealed how an electroless deposit was formed on activated sites.

Equally valuable have been Dr. Weil's publications about the origin and measurement of internal macro- at micro-stress, and in this area he was a leading authority. His observations also explained why deposits have a high density of dislocations, resulting in hardness and low ductility.

In all his years of research, Dr. Weil authored numerous technical articles, and he was asked to write the treatises on electroless and electrolytic plating for the Encyclopedia of Science and Technology. He was co-author with Dr. Read of the chapter "Metallurgical Principles" in Modern Electroplating, and was co-editor of The Proceedings of the Symposium on Electrocrystallization presented by the Electrochemical Society in 1981. He also served on the Editorial Board of Surface Technology.

Dr. Weil was honored as the first recipient of the Research Award of the Electrodeposition Division of the Electrochemical Society in 1979. In addition to his outstanding research contributions to the field of electrodeposition, he was cited as being instrumental in the organization of annual conferences on this topic at Penn State.

Dr. Weil enjoyed a long and prosperous relationship with the AES/AESF, and shared his knowledge in presentations for members of the society's Newark, Detroit, and Boston Branches. In 1970, he received the John J. Hanney Memorial Award for the best paper on copper plating presented at the annual conference, and he presented numerous papers at AES/AESF symposia in recent years. He served as Director of AES/AESF Research Projects 22, 30 and 38, and prepared an Illustrated Lecture to explain in simplified terms the results of this research on structure/property relationships of electrodeposits.